CZECH TECHNICAL UNIVERSITY IN PRAGUE

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Circuit Theory

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MIMO techniques for xDSL

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1 CURRENT SITUATION OF THE STUDIED PROBLEM

Broadband access technologies have the greatest share of global internet access. Growing connection requirements strengthen the broadband technologies for years while the amount of its deployment grown too. Present supply of the broadband technologies offers wireless, wire-line and optical fiber technologies capable of superior data throughput. The first category is mostly represented by a Cellular broadband networks and also Satellite or wireless broadband internet services. Wire-line technologies include popular Digital subscriber lines (DSL) and Cable (TV coaxial) broadband. The most promising category is established on Passive Optical Networks (PON) and ability of optical connection to customer premises.

Optical networks in broadband context slowly increase its amount of deployment. Since the mass transition to this excellent interconnecting media will take its time, other transitional connecting solutions have to be implemented. Intermediate scenario proposes mixed network architecture where the optical fiber interconnection is consecutively planted from top of the network and the "last mile" retains former broadband technologies like DSL, Cable etc. In other words, the optical fiber ends somewhere near to the customer premises in the last Optical network unit (ONU) which could be placed nearby curb or a in a neighborhood. Settled terminology for such mixed network connection is: Fiber To The Curb (FTTC) and Fiber To The Neighborhood (FTTN). Pure passive optical network (PON) would be introducing the feature of Fiber To The Home (FTTH) or Fiber To The Premises (FTTP).

Using former (non optical) broadband technologies at the last mile of the mixed network moderates the optical network transition cost and utilizes already planted structures which can be otherwise operational for another decades. Life span of metallic cables is several decades for example. Network improvement achieved by the fiber optics also puts higher requirements on the non-optical broadband part in order to keep overall network improvements at higher grade. Considering this the non-optical broadband technologies need continuous enhancements until there will be demand for mixed telecommunication networks.

Vectored transmission for DSL systems [20] was the first proposed method that is established on MIMO basis [38]. The *vectored DMT (VDMT)* targets the unbonded DSL systems where the clear MIMO view can not be applied due to lack of end users co-location. Apart from this drawback the VDMT, incorporating general multi-user view, is able to eliminate the FEXT by precoding and interference cancellation in both up- and down-stream directions. A coordinated group of transceivers sharing one binder (binder group) is the particular target in DSL system and self-FEXT affecting the binder group is major performance spoiler. The VDMT method employs joint signal processing of all signals at either receiving side (for upstream) or transmitter side (for downstream). Hence it is mandatory to keep the CO transceivers collocated and controller by a single entity.

Application of MIMO approach coordinating both transmitter and receiver

sides on DSL bonded system was proposed in [3]. This *gigabit DSL (GDSL)* concept exploits wireless MIMO technique of channel diagonalization with use of the singular value decomposition. The authors of [3] utilized thoroughly constructed binder channel model [2] that precisely embodies a number of TP wire-lines bonded in binder cable with their direct and cross-talk channel responses.

Later contributions to research of MIMO techniques on DSL systems suggested to exploit common mode concept of TP wire-lines excitation. Traditional scheme of electronic circuits responsible for TP excitation is a balanced circuit driving the symmetric wiring. This approach – *differential mode (DM)* arisen with the concept of twisting pairs in effort to decrease unwanted ingress to circuit and to improve transmission path electrical parameters. The *common mode signaling (CMS)* breaks this concept and use unbalanced circuits that drives connected wiring asymmetrically. Instead of using N differential mode channels over the N twisted wires (TP), the same number of TP is used as $2N$ channels in the common mode. Doubling of channels number is conditioned by presence of electrical ground conducting, the cable shielding for example. If there is no electrical shielding in the cable, one wire supplies ground conducting function and thus total number of available CMS channels is decreased to $2N - 1$. Another advance came after in using both differential and common modes at once to excite TP bonded in the DSL system cable. This approach reveals even more channel "dimensions" than common mode itself and it has been shown that this mixed approach provides data-rates significantly higher.

Authors of [11] summarize current achievements with CMS and compare them to DM achievements on later VDSL2 systems. Presented results show major data-rate increase with CMS enabled that reach from 50 to 80% data-rate boost and increase greater than 80% boost in case of CMS and DM mixed.

The CMS approach can be used within either bonded DSL system with full MIMO coordination or unbonded DSL system with Vectored DMT. The bonded DSL system was evaluated in previous section in GDSL method [3].

Unbalanced circuit excitation of CMS have indeed serious disadvantage. Radiated energy causing cross-talks to other possible system is substantial and it would disable them in practice. Reasonable setup of both coexisting systems with use of VDMT techniques might solve this cross-talk drawback [11].

Variety of non-MIMO DSL transmission issues are still the subjects of continuing discussions. For example systems dealing with insufficient cyclic prefix (ADSL in particular) were analyzed and techniques that can manage rising interferences (ISI, ICI) were proposed. The *peak-to-average power ratio (PAPR)*, known issue of wireless systems, can be managed within the DSL systems with some improvements in signal transmission. Prevailing issues are the impulsive noise and alien cross-talk impairments. Models and measurements of impulsive noise variations were collected during DSL era. Even such unpredictable phenomenon can be more often mitigated with application of later research. The alien cross-talk elimination success strongly depends on analyzed systems, but is should be easier task than impulsive

noise elimination. With arise of MIMO DSL techniques, the alien cross-talk gained on its significance. The alien cross-talk elimination together with ongoing techniques proposing better power allocation for DSL MIMO systems are introduced later in this section.

Multi-user view brought to DSL systems left opening for wireless techniques other than those discussed lately. The method in question is the *code division multiple access (CDMA)* that was lately proposed to DSL systems. The CDMA basically provides a multiple access of users using mutually orthogonal sequences that allow to distinguish particular user from others at receiver. Moreover the sequences are spanning several sampling periods and thus they spread carried information in time. In other words, they provide code diversity. Robustness of the CDMA within wireless environment is the main advantage, but it is bought back with a loss of immediate channel data-rate due to time spreading. Several authors were concerned about CDMA application in DSL systems [45, 12], while early studies of code division multiplexing were done for example by [25]. The authors of [45] investigate application of the complete complementary multi-carrier CDMA within VDSL2 system with GDSL technique enabled. Their CDMA modified GDSL system shown exceptionally good theoretical system capacity and by that it can support 1 Gbit/s data-rate over 220 m long single TP. Time spreading scheme extending DMT concept of wire-line communication systems is proposed in [12]. This extension is supported by a finite-granularity loading algorithm that drives the multi-carrier direct-sequence CDMA method. Presented optimal power allocation of this scheme leads to throughput improvement of single user DSL system.

2 AIMS OF THE DOCTORAL THESIS

The main objectives of the thesis and the related research are to improve state-of-the-art techniques in the *digital subscriber line (DSL)* systems and to develop a novel method operating on telecommunication network physical layer of DSL systems. The new method is based on the application of the *multiple-input multiple-output (MIMO)* principles commonly used in todays wireless communication systems. It results in direct application of the new technique exploiting MIMO features in future implementations of the DSL physical layer.

Target DSL systems are the *very high speed digital subscriber lines (VDSL)* and the *asymmetric digital subscriber line (ADSL)* standardized by the International Telecommunication Union within the recommendations G.993.1–G.993.5 [29, 30, 32] for the VDSL and G.992.1–G.992.5 [27, 28, 31] for the ADSL, respectively. Transmission media of these DSL technologies is copper-made wiring known as the *twisted pairs (TP)*.

The DSL physical layer consists of a variety of communication processes but the attention is payed to those concerning digital signal processing. These processes include: bit-by-bit or symbol-by-symbol delivery by means of information transmission techniques, flow control and synchronization, modulation, channel coding, multiplexing, electromagnetic spectrum frequency allocation and signal strength specification, equalization filtering, training sequences, pulse shaping, providing of multiple access and multi-user coordination.

The MIMO techniques in general provide beneficial improvement of transmission performance or advance multiple-user access to the transmission media. This particular area corresponds to the DSL physical layer processes mentioned above with emphasis on multiplexing, signal transformation, multiple access and multi-user coordination.

The proposed method will be verified by experiments in a standardized simulation environment. The results will be represented by the key properties describing transmission of information under varying channel conditions. The experimental results will be compared to reference simulation results obtained without application of the proposed method and within the same environment and conditions. To support the validity of the proposed method, the experiment results using digital representation of a real transmission media will be presented.

To summarize the objectives of the dissertation, the list of particular aims to be achieved is provided as follows:

1. To develop a new method exploiting the MIMO *space-time block code (STBC)* technique applied to the corresponding part of the physical layer of the DSL systems.

2. To show that the proposed method improves either transmission performance or provides multiple-user access to the transmission media.

3. To present the proof of concept and to verify the proposed method by results evaluation in a standardized simulation environment.

3 WORKING METHODS

Proposed scheme of the STBC MIMO application to a single DSL link employs a MIMO view of the DMT subcarriers in frequency-time manner, which is in contrast with general space-time MIMO view known from wireless transmission environment. Adopted concept of information diversity provided by STBC that allows error performance improvement is not broken with application to DMT subcarriers with the assumptions that the subcarriers are independent and a non-alien FEXT is only present crosstalk.

Two methods providing scheme setup by selection of DMT subcarriers for the STBC encoding are proposed. The first method directly targets the increase of error performance and the subcarriers selection is driven by subcarrier's error rate. Within this method, the subcarriers are STBC encoded in the case where their error rate exceeds a given threshold. The second method applies the STBC encoding on subcarriers, which were disabled by bitloading due to insufficient information capacity. The first method is applicable in general and the second is targeted to DSL channels with poor SNR conditions at a non-negligible number of subcarriers.

Presented concept of STBC application allows to be applied simultaneously to different users, but the cross-talks from users are not managed.

4 RESULTS

The experiments were performed using both referential setup utilizing the channel modeled by simple linear-phase FIR filter and the "real channel" setup utilizing the channel based on real measurements of DSL metallic cable.

The referential experiments for the first method, which applies the error feedback algorithm, proved the expectation of a significant error rate decrease using the proposed MIMO STBC scheme on the single DSL link transmission.

The referential experiments for the second method, which utilizes subcarriers disabled by regular bitloading algorithm, have shown the expected data rate increase. This method has also proven the validity of the bitloading lower bound for subcarrier selection with SNR margin. Due to the SNR margin strongly decrease overall error rate, the experiment did not achieved statistically valuable results (we have obtained zero error rate for 10^7 transmitted bits). Further experiments ("inserted ones"), which provided statistically valuable results with adequate amount of errors, have shown that the MIMO STBC application significantly increases the data rate at the cost of adequately small error rate increase. This increased error rate level was small enough and close to the system's target error probability.

The "real channel" error feedback experiments have shown significant error rate decrease at the cost of small data rate decrease for higher SNR cases. Evaluated setup has shown satisfying results, which supports theoretical expectations.

The bitloading feedback algorithm was heavily tested within the "real channel" experiments. The achieved results have confirmed validity of the proposed STBC application scheme with bitloading feedback algorithm in the second variant, which blindly utilizes all unused subcarriers. The application of STBC is always a trade-off between the higher data rate and the lower error rate. The data rate is always higher than that of original DSL and error rate is lower than the highest error rate of the full one-bit transmission on unused subcarriers.

Within this experiment setup, the LCRA algorithm for discrete loading was also evaluated. As the LCRA utilizes subcarrier information capacity in full range, the bitloading feedback results were expected to be flawed. The experiments shown that the LCRA does not affect the system performance of the bitloading feedback applied on a system with SNR margin.

5 CONCLUSION

The main objectives of the thesis and the related research are to improve state-of-the-art techniques in the *digital subscriber line (DSL)* systems and to develop a novel method operating on telecommunication network physical layer of DSL systems. The new method is based on the application of the *multiple-input multiple-output (MIMO)* principles commonly used in todays wireless communication systems. It results in direct application of the new technique exploiting MIMO features in future implementations of the DSL physical layer.

Target DSL systems are the *very high speed digital subscriber lines (VDSL)* and the *asymmetric digital subscriber line (ADSL)* standardized by the International Telecommunication Union. Transmission media of these DSL technologies is copper-made wiring known as the *twisted pairs (TP)*.

In the first chapter, we introduced broadband access considerations and we figured out the motivation to keep the current DSL broadband technologies in progress. In the next chapter, we gave an introduction to basic concepts of DSL technology, set up the system model and gave a overall state of the art summary of enhanced DSL techniques. Further, we summarized the relevant MIMO concepts used in wireless systems.

In the fourth chapter, we proposed the scheme of MIMO STBC application on single DSL link and proposed two strategies to optimize the DSL transmission. Proposed scheme employs a MIMO view of the DMT subcarriers in frequency-time manner, which is in contrast with general space-time MIMO view known from wireless transmission systems. Adopted concept of information diversity provided by STBC that allows error performance improvement is not broken with application to DMT subcarriers with the assumptions that the subcarriers are independent and a non-alien FEXT is only present cross-talk.

Two methods, which apply proposed strategies, were presented. They provide the scheme setup by selection of DMT subcarriers for the STBC encoding. The first method directly targets the increase of error performance and the subcarriers selection is driven by subcarrier's error rate. Within this method, the subcarriers are STBC encoded in the case where their error rate exceeds a given threshold. The second method applies the STBC encoding on subcarriers, which were disabled by bitloading due to insufficient information capacity. The first method is applicable in general and the second is targeted to DSL channels with poor SNR conditions at a non-negligible number of subcarriers. Presented concept allows to be applied simultaneously to different users, but the cross-talks from users are not managed.

In the fifth chapter, we presented experimental results for referential channel model and for channel based on real measurements of DSL metallic cable – "real channel".

The referential experiments for the first method, which applies the error feedback algorithm, proved the expectation of a significant error rate decrease using the proposed MIMO STBC scheme on the single DSL link transmission.

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The bitloading feedback algorithm was heavily tested within the "real channel" experiments. The achieved results have confirmed validity of the proposed STBC application scheme with bitloading feedback algorithm in the second variant, which blindly utilizes all unused subcarriers. The application of STBC is always a trade-off between the higher data rate and the lower error rate. The data rate is always higher than that of original DSL and error rate is lower than the highest error rate of the full one-bit transmission on unused subcarriers.

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Publications of the author

List of publications relevant to the thesis

Papers in proceedings

[B1] Mazanec T.: Simulator of ADSL Physical Layer ,*Technical computing Prague 2007. 15th annual conference proceedings*, Praha, 14.11.2007 – 100 %

[B2] Mazanec Tomáš : Advanced Algorithms for Equalization on ADSL Channel , *Technical computing Prague 2006. 14th annual conference proceedings*, p. 68-75 , Prague, 26.10.2006 – 100 %

[B3] Mazanec T., Heřmánek A., Matoušek R.: Model of the transmission system of the reconnaissance system Orpheus , *Technical Computing Prague 2005 : 13th Annual Conference Proceedings*, p. 1-4 , Praha, 15.11.2005 – 50 %

Research reports

[C1] Mazanec T.: Použití MIMO technik pro xDSL, ÚTIA, Praha, Research Report 2305, 2011 – 100 %

[C2] Mazanec T., Heřmánek A. : ADSL - ekvalizační techniky, ÚTIA, Praha, Research Report 2184, 2007 – 100 %

[C3] Mazanec T., Heřmánek A.: Simulace ekvalizérů TEQ pro ADSL toolbox: výsledky experimentů, ÚTIA AV ČR, Praha, 2007, Research Report 2194 – 100 %

Software outputs and hardware prototypes

[D1] Mazanec T., Heřmánek A.: Matlab ADSL Toolbox ver. 11, 2007, software – 100 %

[D2] Mazanec T., Heřmánek A.: Simulace ADSL downstream přenosu Webová aplikace, ÚTIA AV ČR, Praha, 2007, software – 100 %

[D3] Mazanec T., Heřmánek A.: Simulátor fyzické vrstvy ADSL modemu, ÚTIA AV ČR, Praha, 2007, software – 100 %

List of other publications

Journal papers

[A1] Mazanec T., Brothánek M. : FPGA implementace LMS a N-LMS algoritmu pro potlačeni akustického echa , Akustické listy vol.10, 4 (2004), p. 9-13 2004 – 50 %

Papers in proceedings

[B4] Mazanec T.,Heřmánek A., Kloub J. : Heterogeneous Platform for Stream Based Applications on FPGAs, accepted for: *Proceedings of the 21st International Conference on Field Programmable Logic and Applications – FPL 2011*, Chania, Crete, GREECE, 5.-7.9. 2011 – 30 %

[B5] Mazanec T.,Heřmánek A., Kamenický J. : Blind image deconvolution algorithm on NVIDIA CUDA platform , *Proceedings of the 13th IEEE Symposium on Design and Diagnostics of Electronic Circuits and Systems*, Vienna, AT, 14.-16.04.2010 – 30 %

Software outputs and hardware prototypes

[D4] Mazanec T.: Application of CUDA in DSP: Implementation of FIR filter and Cross Ambiguity Function, 2009, software – 100 %

[D5] Mazanec T., Kloub J., Heřmánek A. , Tichý M.: DVB-T2 Receiver Prototype: Physical Layer, 2009, prototype – 30 %

[D6] Mazanec T. Heřmánek A. , Tichý M.: DVB-T2 Receiver: Physical Layer Simulator, 2009, software – 30 %

[D7] Mazanec T., Kloub J., Heřmánek A.: HW Platform for Software Defined Radio, 2007, prototype – 50 %

To our knowledge, there has been no response to the publications of the author. Listed journals and proceedings have no impact factor.

SUMMARY

The main objectives of the thesis and the related research are to improve state-of-the-art techniques in the *digital subscriber line (DSL)* systems and to develop a novel method operating on telecommunication network physical layer of DSL systems. The new method is based on the application of the *multiple-input multiple-output (MIMO)* principles commonly used in todays wireless communication systems. It results in direct application of the new technique exploiting MIMO features in future implementations of the DSL physical layer.

In the first section, we introduce broadband access considerations and we figure out the motivation to keep the current DSL broadband technologies in progress. Further, we give an introduction to basic concepts of DSL technology, set up the system model and give a overall state of the art summary of enhanced DSL techniques. Further, we summarize the relevant MIMO concepts used in wireless systems. Goals of this thesis are defined in the third chapter. In the fourth chapter, we propose the scheme of MIMO STBC application on single DSL link and propose two strategies to optimize the DSL transmission. The first strategy applies the scheme on DMT subcarriers exhibiting error rate over a given threshold. This results in error rate improvement. The second strategy applies the scheme on unused DMT subcarriers, which increases data rate. In the fifth chapter, we present experimental results for referential channel model and for channel based on real measurements of DSL metallic cable. Finally, in chapter six, we summarize the conclusions and give suggestions for further research.

SHRNUTÍ

Cílem předložené disertační práce je výzkum v oblasti moderních DSL systémů a návrh algoritmických metod na úrovni fyzické vrstvy zvyšujících kvalitu přenosových parametrů. Navržená metoda využívá principů MIMO běžně známých v moderních bezdrátových komunikačních systémech. Výsledkem práce je přímá aplikace inovativní MIMO metody na fyzickou vrstvu DSL systému.

V první části práce, je presentován současný stav širokopásmových sítí a je presentována motivace k dalšímu rozvoji DSL systémů. Následně je uveden úvod do DSL technologií, model systému a celkový přehled pokročilých DSL technik a MIMO metod pro bezdrátové komunikace. Závěrem úvodní části práce jsou specifikovány cíle práce.

V druhé části práce, začínající čtvrtou kapitolou, je navržena metoda využití časo-prostorového kódování pro jednouživatelský DSL přenos (ADSL, VDSL). Pro tuto metodu byly aplikovány dvě různé strategie optimalizace přenosových parametrů. První strategie využívá tónů, které vykazují chybovost vyšší než specifikovaný práh a vede tudíž ke snížení celkové chybovosti přenosu. Druhá strategie využívá tóny, specifikované bit-loading algoritmem jako nepoužité z důvodu nedostatečné přenosové kapacity. Tato strategie vede ke zvýšení datového přenosu.

V páté kapitole jsou presentovány výsledky experimentů obou strategií provedené jak na modelovém kanálu, tak na naměřeném reálném kanálu. V šesté kapitole je souhrn dosažených výsledků práce.